13.—Sand Fulgurites from Western Australia

by J. E. Glover[1]

Manuscript received 19 February 1974; accepted 19 March 1974

Abstract

Fulgurites have been recovered from sand at Willetton, East Victoria Park and Coopers Sandpit, Canning Vale, all near Perth, and from Thangoo Station, near Broome. The Willetton material consists of tube, wall and flange fragments of very light grey vesicular lechatelierite having a refractive index of 1.461 and a silica content of 99.4%. Partly fused quartz grains are embedded in the rough dull outer walls, but are absent from the botryoidal, shiny, inner surfaces. The data accord with an origin due to fusion of sand by lightning. Irregularly shaped black bodies about one mm in diameter scattered in the glass are higher in Fe_2O_3, TiO_2 and MnO_2 than surrounding lechatelierite and probably represent glass stained by oxides from heavy minerals in the parent sand. The other fulgurites resemble the Willetton material mineralogically and texturally, but contain a higher proportion of cylindrical pieces.

An artificial fulgurite from Cottesloe, consisting of vesicular lechatelierite, is compared with the natural fulgurites. It is broader, lacks a central lumen and flanges, and most of its embedded sand grains are altered to cristobalite.

Introduction

The term fulgurite (from the Latin *fulgur*, lightning) has long been applied to tube-like glassy bodies found on and near the Earth's surface and supposedly formed from sand or rock melted by lightning strikes. The term was first used in 1790 (see Harland & Hacker, 1966) but the bodies had been noted earlier. Many fulgurites have been observed since, and there is a comprehensive discussion by Frondel (1962), who lists the significant references to that time. Artificial fulgurites (Petty, 1936; Fenner, 1949; Raeside, 1968), pseudofulgurites of opal (Read, 1951), and palaeofulgurites (Harland & Hacker, 1966) have also been described.

In Australia, fulgurites and possible fulgurites are known from Moreton Island and Springsure, Queensland (Connah, 1947; Fenner, 1949), Bondi and Macquarie Harbour, New South Wales (Baker, 1959), numerous localities in western Victoria (Fenner, 1949; Beasley, 1963), Oodnadatta, Farina and Mt Remarkable, South Australia (Fenner, 1949), Tempe Downs, Northern Territory (Baker, 1953*a*), and several localities in the Yilgarn Block, Western Australia (Simpson, 1931; Trendall, 1964). Artificial fulgurites from Cottesloe and Welshpool, Western Australia, caused by high voltage electric currents, were collected by Professor E. de C. Clarke and described by Fenner (1949). Previously undescribed natural fulgurites from Thangoo Station, southeast of Broome*, and from Kent Street, East Victoria Park†, about 5 km southeast of Perth, have been recognized in the rock store of the Geology Department, University of Western Australia.

This paper describes lechatelierite fragments discovered by the author at Willetton and at Coopers Sandpit, Canning Vale, both in the Perth area, and also describes the fulgurites from Thangoo Station and East Victoria Park in the Geology Department repository. The material is compared with the artificial Cottesloe fulgurite**, for which some new data are given, and the West Popanyinning fulgurite of Simpson††. It is shown that all the newly described material can be categorized as classic tubular or sand fulgurites and that they resemble the West Popanyinning fulgurite, for which an origin by lightning fusion of sand is accepted.

Location and stratigraphic position of the fulgurites

Some five hundred fulgurite fragments were recovered from a cleared area on the southern edge of Leach Highway where it joins High Road, Willetton, about 10 km southsoutheast of Perth, and one fulgurite fragment was collected from Cooper's Sandpit in Ranford Road, Canning Vale, about 17 km southsoutheast of Perth (see Fig. 1). At each locality the material was in a fixed dune of the Bassendean Dune System of McArthur & Bettenay (1960). The dunes had been cleared of vegetation and soil to a depth of 30 cm or more, and it is not known whether the clearing, or earlier movement in the dune, caused the fulgurite fragmentation. The abundant Willetton material is being exposed by deflation, because more is found with succeeding visits. The smaller flake-like fragments are probably moved fairly easily by the wind. The Willetton exposure will be overbuilt shortly, and the discovery site at Coopers Sandpit has already been excavated and destroyed.

[1] Geology Department, University of Western Australia, Nedlands, W.A. 6009.

* University Geology Department No. 42016
† University Geology Department No. 1158
** University Geology Department No. 12141
†† University Geology Department No. 12158

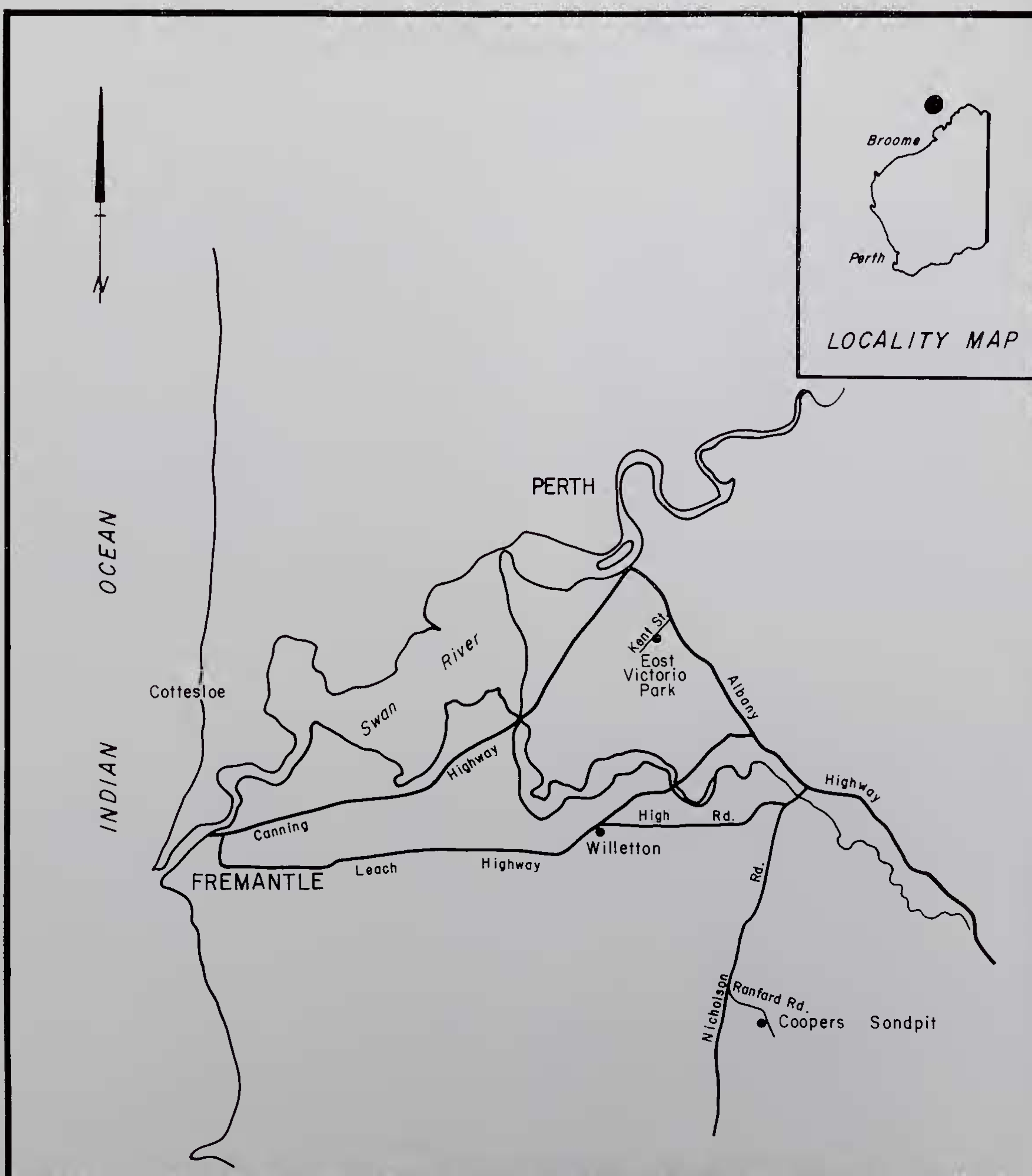

Figure 1.—Map of the Perth area showin g fulgurite localities. Scale: 10 km = 6.3 cm.

The East Victoria Park material is recorded in Geology Department files as having been presented by Mr H. R. Gildard, of 80 Kent Street, in 1935. It was said by Mr Gildard to have been dug out of a hole about 2 metres below the surface of his backyard, and to have been in approximately a vertical position. About 30 centimetres were recovered. The map of McArthur & Bettenay (1960) shows that the Kent Street specimen, like the Willetton and Canning Vale material, was in sand of the Bassendean Dune System.

The Thangoo fulgurite was presented to the Geology Department in 1958 by Dr P. E. Playford and is understood to have come from a vegetated sand dune on Thangoo Station, southeast of Broome.

Petrology

The colours and corresponding numerical designations used below refer to the Rock-color Chart distributed by the Geological Society of America (Rock-color Chart Committee, 1963).

Petrography of the Willetton material

About 100 grams of fulguritic material has been collected at Willetton*. Some of the 500 fragments consist of small tubes and some of compressed, highly contorted envelopes open along one or two edges, the latter probably representing broken portions of prominent flanges. Most of the Willetton material, however, encloses no central space and comprises wall fragments about one mm thick and up to about three square cm in area (Fig. 2). All fragments have shiny, somewhat botryoidal inner surfaces and contrasting, dull, jagged exteriors embedded with white, rounded, and subrounded sand grains. The mineral comprising the walls is very light grey (N8) glass with numerous bubbles and a few irregularly shaped, widely dispersed black bodies about one mm in diameter.

Under the microscope the fragments are seen to consist mainly of colourless vesicular glass with bubbles ranging from 0.001 mm to 0.04 mm in diameter. The bubbles fall into two categories. The small cavities that have not been breached during sectioning are apparently gas-filled, and their very low refractive index relative to the surrounding glass is emphasized by their black margins. The larger cavities have been breached and filled with a medium of refractive index 1.54, and these cavities show no black borders. Bubbles tend to be oriented with their long axes normal to the plane of the fulgurite fragment, or to the lumen where present. Most of the bubble cavities are clear, but a few contain some finely divided, indeterminate pale brown mineral. The photomicrograph illustrating the texture of the fulgurite (Fig. 3) bears a striking resemblance to that used by Julien (1901, Fig. 2) in his illustration of a Polish sand fulgurite.

* University Geology Department No. 72124

Figure 2.—Fragments of the Willetton lechatelierite, showing (top) the shiny somewhat botryoidal inner surface, and (bottom) the dull rough outer surface. Note the small black portions. The upper fragment is about 2 cm long.

The glass shows two types of boundary in transverse section. One boundary, corresponding to the inner surface, is smooth, and the other, corresponding to the rough dull outer surface, is uneven. The glass toward the uneven boundary commonly has a rather granular texture and locally grades into faintly anisotropic material. Discrete sand grains are embedded in the outer wall, but are not shown in Figure 3. These grains have an unusual appearance under the microscope and commonly consist of biaxial quartz with curved cracks filled with glass. Some individual grains range from an intimate, turbid mixture of quartz and glass on one side, to clear colourless glass on the other.

The refractive index of the glass measured with sodium light is 1.461 ± .002, close to that given by Winchell & Winchell (1956, p. 250) for lechatelierite, and within the range of values reported by Frondel (1962, p. 322) for fulgurite glasses.

The black bodies visible in handspecimen are formed of irregularly shaped, brown to black opaque cores and concentrations of wisps that grade outward, with increasing translucency, into brown and pale brown glass. Black bodies of about the same size and distribution are evident in some fulgurites photographed by Fenner (1949), notably those from South Australia. They have been mentioned by other authors (see, for example, Petty, 1936, p. 191 and Frondel, 1962, p. 322), and Simpson (1931, p. 146) refers to "small areas . . . darkened by the presence of iron silicate, etc." They are evidently common in tubular sand fulgurites, but have excited little comment or investigation.

Figure 3.—Photomicrograph of thin section of fulgurite from Willetton. The smooth inner surface is on the left, and contrasts with the rough outer surface on the right. Large vesicles tend to be elongated normal to the lumen, and small bubbles show up as almost solid black circles. Length shown = 2 mm.

Chemistry of the Willetton material

The Willetton glass is lechatelierite consisting of 99.4% SiO_2, with small amounts of titania and other oxides (see Table 1 for comparative analyses of Western Australian glasses). To establish the nature of the scattered black bodies some of the glass was crushed and black material was handpicked for analysis. Few of the selected crushed fragments consisted of pure black material, and most were contaminated by at least an equal volume of light grey glass. X-ray powder pattern photographs showed no lines, confirming the impression gained from microscopic examination that the black material is not crystalline. Comparative analyses of the dark concentrate and the light grey glass of the fulgurite by the atomic absorption spectrometer showed that TiO_2 was concentrated in the dark material by a factor of 2, Fe_2O_3 by a factor of 4, and MnO_2 by a factor of more than 6. These oxides were probably supplied by heavy minerals in the fused sand, and doubtless account for the dark colour.

Table 1

Analyses of Western Australian vesicular and scoriaceous glasses

	Willetton*	West Popan-yinning**	Widgie-mooltha†	Widgie-mooltha††
SiO_2	99·4	88·46	64·9	59·2
TiO_2	0·14	0·46	0·06	n.d.
Al_2O_3	0·09	6·69	9·12	13·0
Fe_2O_3	0·012	1·16	5·75	9·4
Mn O	0·002	Tr	0·02	n.d.
Mg O	0·0795	0·17	3·27	5·7
Ca O	0·02	0·17	12·0	10·4
Na_2O	0·011	0·01	2·05	2·0
K_2O	0·02	2·68	1·64	1·1
P_2O_5	n.d.	n.d.	0·15	n.d.
Cu	n.d.	n.d.	n.d.	0·01
H_2O+	n.d.	n.d.	0·41	n.d.
Loss on ignition	0·02	....	....	....
	99·8 (approx.)	99·80	99·37	100·8
	N = 1·461	N = 1·465 G 2·21		

* Analyst Labtech Pty Ltd, Job No 5917, Rack No 6250 (combined XRF, Atomic absorption)

** Reported by Simpson (1931, p.146)

† Specimen R851, "fulgurite slag", Widgiemooltha area, Analyst Govt. Chem. Lab, reported by Trendall (1964, p.7)

†† "Fulgurite slag", near Paris Goldmine, Widgiemooltha area, Analyst C. E. S. Davis, reported by Trendall (1964, p.7).

The Willetton sand

The fulgurites are mainly found in white to pinkish grey (N9-5YR8/1) sand near the crest of a fixed dune, but winds sweep the bare patch and small fragments are also found in nearby orange sand (see below). The white sand is well sorted (So = 1.22) and consists mainly (about 99.6%) of subrounded to well-rounded quartz grains with a median diameter of 0.28 mm. Some of the quartz is practically free of inclusions, and some contains minute inclusions of black opaque minerals, leucoxene, rutile, tourmaline, hypersthene, zircon, probable apatite and fluid. Heavy minerals separated in bromoform from a sample of sand made up 0.44% by weight and consist mainly of ilmenite and leucoxene (see Table 2).

Also near the top of the dune, and containing a few small fulgurite fragments, is some very pale orange to greyish orange (10YR8/2-10YR 7/4) sand. This sand is as well sorted as the white sand, yielded an almost identical crop of heavy minerals (0.45% by weight), and seems to differ only by the discontinuous film, apparently of limonite and hematite, on many of the grains. The concentration of fulgurite fragments (particularly the larger ones) in the white sand, and the presence in the glass of embedded white grains but not of orange-coloured grains, shows that the fragments originated in white sand and were recently blown into the orange-coloured sand.

Table 2

Mineralogy of white sand from Willetton

Mineral	Wt%
Quartz	99·56
Ilmenite	0·25
Leucoxene	0·09
Magnetite	0·03
Staurolite	0·02
Kyanite	0·02
Zircon	0·01
Garnet	Trace
Tourmaline	Trace
Rutile	Trace
Spinel	Trace
Andalusite	Trace
Unknown	Trace

Mineralogical source of the Willetton fulgurites

The white sand of the Willetton area would yield a highly siliceous glass if fused and chilled, and the high silica content of the Willetton fulgurites, together with their incorporated partly fused quartz grains, accords with such an origin. TiO_2 (0.14%) is fairly close to the amount calculated for the sand from its mineralogy (0.22%), but Fe_2O_3 (0.012%) is significantly lower than the sand mineralogy would indicate (0.17%). The reason for this apparent discrepancy can only be speculated: iron may have migrated quickly when the quartz fused, or may have been leached out of the glass later.

The Coopers Sandpit material

The material from Coopers Sandpit, Canning Vale*, consists of an irregularly flanged tube about 2.5 cm long with an inner diameter of about 0.7 cm and a variable outer diameter of about 0.9 cm (Figs. 4, 5). The outer walls are rough and uneven, and contain numerous, embedded, white to very light grey (N9 to N8), rounded to subrounded, fine to medium-grained sand grains. The inner walls consist of smooth, shiny, somewhat botryoidal very light grey (N8) glass with a few black stains about 1 mm in diameter. The weight of the specimen is 0.8 grams.

A small fragment was broken from the tube, crushed, and examined microscopically in oils. The material is highly vesicular colourless glass with a refractive index of 1.461 ± .002.

* University Geology Department No 72125

Figure 4.—Side view of fulgurite fragment from Coopers Sandpit, Canning Vale. Note the rough dull outer surface, and smooth bright inner surface. Length of fragment 2.5 cm.

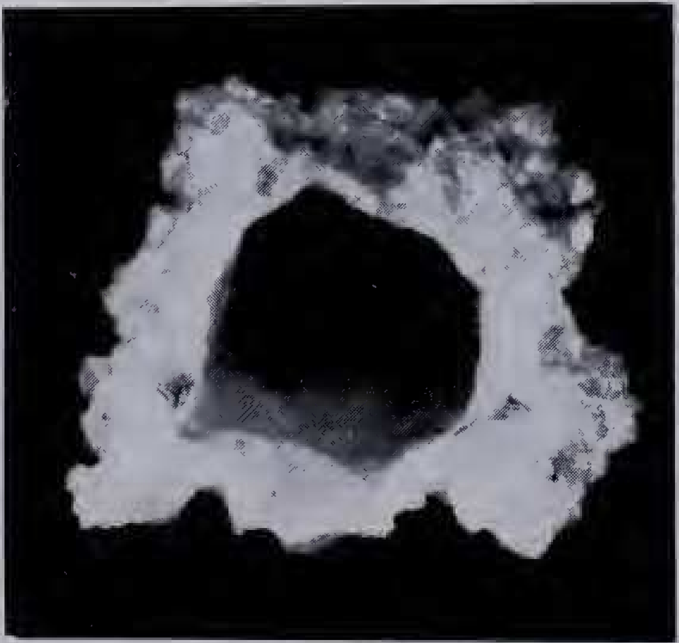

Figure 5.—End-on view of fulgurite fragment from Coopers Sandpit, Canning Vale. The rough, flanged exterior contrasts with the smooth lumen. The lumen has a diameter of about 7 mm.

The East Victoria Park material

This material consists of a tube 5.5 cm long and 1.5 cm wide, with walls about 1 mm thick. The outer surface is light grey (N7) and has a rough feel, but is only slightly flanged. Pale yellowish orange (10YR8/6) to very pale orange (10YR8/2) rounded to subrounded quartz sand grains embedded in the light grey glass give it a speckled greyish orange appearance. The inner surface of the tube consists of shiny, smooth but crinkled, very light grey (N8) to light grey (N7) glass. Irregularly shaped black bodies or stains about one mm in diameter are present in the glass, and can also be seen on the outside. In addition to the cylinder there are thirteen small fragments, and in all, the specimen weighs 6.2 grams.

Some of the material was powdered and examined microscopically in oils. It consists mainly of finely vesicular colourless glass with some attached quartz grains. The refractive index of most of the glass is very close to 1.461 ± .002, but the index is not completely uniform, and a range up to 1.463 ± .002 was noted.

The Thangoo material

The Thangoo material consists of numerous small fragments and two tubular fragments, each about 5 cm long and 2 cm wide, with walls about one mm thick. The outer surfaces are very light grey to light grey (N8 to N7), with a rough feel, but have developed only incipient flanges. These surfaces consist mainly of very well rounded to subrounded sand grains up to one mm in diameter. The inner surface is made up of light grey to medium grey (N7 to N5) shiny botryoidal glass, and a few small irregularly shaped black bodies can be seen in it. The total weight of the material is 27.2 grams.

Microscopic examination of crushed material in oils shows that it consists mainly of colourless, finely vesicular glass with attached quartz sand grains, some of which are turbid where they pass, via an intimate quartz-glass mixture, into clear glass. The glass ranges in refractive index mainly between 1.458 ± .002 and 1.466 ± .002, and most of it is close to 1.461 ± .002.

The bubble cavities are generally clear. A thin section of part of the fulgurite, however, shows bubbles filled with opaque aggregates of a very finely divided mineral that is greyish yellow (5Y8/4) to light brown (5YR5/6) in reflected light. The mineral may have been introduced, but its origin is uncertain.

Main features of the sand fulgurites: a summary

All the material is fragmentary, and has been derived from longer tubes, whose original shapes and dimensions are unknown. The fragments have many common features. All the glass is finely vesicular, is light grey to very light grey (N7 to N8), and contains scattered, irregularly shaped black bodies or stained portions about one mm in diameter. Each fragment has one dull surface with embedded sand grains or partly vitrified sand grains, and one crinkled shiny or vitreous surface. On the dull or outer surface there are incipient to strongly developed winglike projections or flanges parallel to the length of the tube. The refractive index ranges from 1.458 to 1.466, but the most common value is 1.461.

A fragment of the West Popanyinning fulgurite described by Simpson is available for comparison (University Geology Department No. 12158). Its walls have the same structural and textural characteristics, including sand grains embedded on the outside, and projecting flanges. The colour of the shiny botryoidal glass of the lumen is light grey (N7) with scattered black spots, and the refractive index of the highly vesicular glass, according to Simpson (1931) ranges from 1.463 to 1.467 with a mean of 1.465. The West Popanyinning fulgurite was found in clayey, feldspathic sand and is more aluminous and less siliceous than the fulgurites described above. In other respects, however, it is very similar, and clearly deserves to be grouped with them.

Cottesloe artificial fulgurite

One specimen of the artificial fulgurites collected from Cottesloe by Professor E. de C. Clarke and described by Fenner (1949) is housed in the Geology Department, University of Western Australia (Fig. 6). The material formed from the fusion of sand by shorting of electric mains, and is likely to have been subject to a lower voltage maintained for a longer time, than natural fulgurites. The specimen is 18.5 cm long, about 8 cm wide at its widest, and weighs 723.4 grams. The colour of the glass ranges from medium to medium dark grey (N5 to N4), but because the outer surface is encrusted with white to very light grey (N9 to N8), well-rounded sand grains, the overall colour of parts of the outer surface is light grey (N7). The central part is made up of highly vesicular glass with some large cavities, but there is no central lumen. Under the microscope the glass is colourless with dark grey schlieren: its refractive index ranges from 1.461 ± .002, which is fairly common, to 1.466 ± .002. Most of the sand grains of the outer surface have been pseudomorphed by aggregates of cristobalite showing "tile" structure under the microscope. The identity of the cristobalite has been confirmed by X-ray powder photography.

Fenner, who examined several artificial fulgurites, including the Cottesloe specimen, noted that they differ in several respects from natural fulgurites. The tube is thicker and may be practically filled with glass, and the subparallel flanges are absent. It can be added that cristobalite, present in the Cottesloe specimen, was not observed in the natural fulgurites described in this paper.

Figure 6.—Artificial fulgurite from Cottesloe. The light grey areas contain embedded sand grains, most of which have been altered to cristobalite. Length of specimen 19.5 cm.

Origin of the Western Australian sand fulgurites

The arid climate and sparse vegetation in parts of Australia have probably favoured the preservation and allowed the exposure of many kinds of natural glass that tend to be destroyed or covered with soil in more humid and highly vegetated countries. The sand or tubular fulgurites described above can generally be distinguished by their shape, texture, composition or geological setting from other Australian natural glasses. The latter include volcanic glass; drift pumice from outside Australia (Sutherland, 1965; Bryan, 1968); pseudotachylite from fault zones (not uncommon, but poorly documented: see Francis, 1972, p. 35); australite glass of extra-terrestrial origin (Baker, 1959); glass formed by meteorite impact (Spencer, 1933); and glasses formed by burning coal or vegetation (Baker & Gaskin, 1946; Baker, 1953*b*, 1964; Trendall, 1964). It should be said that there is no unanimity in applying the origins just listed to some of the glasses, and in particular the origin of so-called Darwin glass is by no means finalized. Trendall (1964) erected an additional category, that of "fulgurite slag", for material formed by the fusion of soil by lightning, and he included in it the scoriaceous slaggy material collected on the Yilgarn Block (see Table I) and some of the glasses for which an origin due to melting by fire had been suggested by others. Subsequent evidence however (Trendall *pers. comm.*) throws doubt on the origin of the Yilgarn slags. As indicated, the material described in this paper is rather different: it adds nothing to our knowledge of the other glasses, and they will not be discussed further.

The fused sand grains and high silica content of the newly described Western Australian fulgurites practically prove derivation from the sand in which they were found. The sand was almost certainly melted by lightning because temperatures reached in lightning flashes (Loeb, 1949, p. 22; Schonland, 1964, p. 98) are far higher than the 1800°C supposedly necessary for quick fusion of quartz (Rogers, 1946), whereas temperatures attained by natural fires seem normally to be over 1000°C lower (see Beadle, 1940). Moreover, these fulgurites are similar in form and texture to that described by Simpson (1931), which was recovered from sandy ground shortly after a lightning strike. Simpson's fulgurite extended downward for about a metre, and seems to have had the same orientation as the Kent Street fulgurite. A similar fulgurite, collected after an observed lightning strike, was recorded by Fenner (1949, p. 128). These examples independently supplement extra-Australian reports of fusion by lightning (Pfaff, 1822; Wicke, 1859; Van Bastelaer, 1883; Wood, 1910) and together constitute an impressive body of evidence.

A great deal has been written about the tubular, branching shape of sand fulgurites. The central lumen and numerous vesicles are commonly attributed to the thermal expansion of air and vapour from water trapped in the sand, and any flattening of the tube to the pressure of the surrounding sand while the glass was plastic. The abundant Willetton material seems to represent fragments of highly flanged tubes whereas the other fulgurites consist of broken tubes on which the flanges were less prominent. The tendency for vesicles to be elongated normal to tube walls fits the concept of outwardly moving gas during thermal expansion.

It has been suggested (Lewis, 1936, p. 57; Fenner, 1949, p. 138) that fulgurites owe their shape to fusion of sand around the roots of trees or plants struck by lightning. The root would be carbonized and might, with downward burning, smoulder to ash. Trendall (1964) discussed this aspect, and concluded that most tube fulgurites formed around roots. The fulgurites described above provide no evidence on this point.

Conclusions

The fulgurites recorded in this paper are of the classical tube or sand fulgurite variety, and formed from sand fused by lightning. The abundance of lightly vegetated, sandy country in Western Australia practically ensures that many similar fulgurites remain to be found.

References

Baker, G. (1953*a*).—Natural sinters from *Mt. Remarkable* and Tempe Downs. *Trans. R. Soc. S. Aust.*, 76: 27-33.

Baker, G. (1953*b*).—Naturally fused coal ash from Leigh Creek, South Australia. *Trans. R. Soc. S. Aust.*, 76: 1-20.

Baker, G. (1959).—Tektites. *Mem. nat. Mus. Vict.*, 23: 1-313.

Baker, G. (1964).—Hay-silica glass from Gnarkeet, Western Victoria. *Mem. nat. Mus. Vict.*, 26: 21-45.

Baker, G., and Gaskin, A. J. (1946).—Natural glass from Macedon, Victoria, and its relationships to other natural glasses. *J. Geol.*, 54: 88-104.

Beadle, N. C. W. (1940).—Soil temperatures during forest fires and their effect on the survival of vegetation. *J. Ecol.*, 28: 180-192.

Beasley, A. W. (1963).—A fulgurite from Karnak, Western Victoria. *Mem. nat. Mus. Vict.*, 26: 11-19.

Bryan, W. B. (1968).—Low-potash dacite drift pumice from the Coral Sea. *Geol. Mag.*, 105: 431-439.

Connah, T. H. (1947).—A fulgurite from Moreton Island. *Qd Govt Min. J.*, 48: 20.

Fenner, C. (1949).—Sandtube fulgurites and their bearing on the tektite problem. *Rec. S. Aust. Mus.*, 9: 127-142.

Francis, P. W. (1972).—The pseudotachylite problem. *Comments Earth Sci.: Geophys.*, 3 (2): 35-53.

Frondel, C. (1962).—*"The System of Mineralogy. III Silica Minerals"*. (7th Ed.) (Wiley, New York.).

Harland, W. B., and Hacker, J. L. F. (1966).—"Fossil" lightning strikes 250 million years ago. *Adv. Sci.*, 22: 663-671.

Julien, A. A. (1901).—A study of the structure of fulgurites. *J. Geol.*, 9: 673-693.

Lewis, A. D. (1936).—Fulgurites from Witsands on the southeastern borders of the Kalahari. *S.A. Geogr. Jl.*, 19: 50-57.

Loeb, L. B. (1949).—The mechanism of lighting. *Sci. Am.*, 180 *(2)*: 22-27.

McArthur, W. M., and Bettenay, E. (1960).—The development and distribution of the soils of the Swan Coastal Plain, Western Australia. *C.S.I.R.O. Soils Publ.*, 16.

Petty, J. J. (1936).—The origin and occurrence of fulgurites in the Atlantic Coastal Plain. *Am. J. Sci.*, 31: 188-201.

Pfaff, C. H. (1822).—Beobachtete Enstehung einer Blitzröhre durch den Blitz. *Ann. Phys.*, 72: 111.

Raeside, J. D. (1968).—A note on artificial fulgurites from a soil in south-east Otago. *N.Z. Jl. Sci.*, 11: 72-76.

Read, J. J. (1951).—The nature and composition of pseudofulgurite tubes discovered in sand dunes near Levin. *N.Z. Jl. Sci. Technol.* 32 Sec B (4): 1-7.

Rock-color Chart Committee (1963).—*"Rock-color Chart"* (Geol. Soc. Am., New York).

Rogers, A. F. (1946).—Sand fulgurites with enclosed lechatelierite from Riverside County, California. *J. Geol.*, 54: 117-122.

Schonland, Sir Basil (1964).—*"The Flight of Thunderbolts"* (2nd Ed.) (Clarendon Press, Oxford).

Simpson, E. S. (1931).—Contributions to the mineralogy of Western Australia—Series VI. *J.R. Soc. West. Aust.*, 17: 137-149.

Spencer, L. J. (1933).—Meteoric iron and silica-glass from the meteorite craters of Henbury (Central Australia) and Wabar (Arabia). *Mineralog. Mag.*, 23: 387-404.

Sutherland, F. L. (1965).—Dispersal of pumice, supposedly from the 1962 South Sandwich Islands eruption, on southern Australian shores. *Nature, Lond.*, 207: 1332-1335.

Trendall, A. F. (1964).—Slaggy siliceous glass occurring naturally on the surface at various localities in the southern part of Western Australia. *Rec. geol. Surv. West. Aust.*, 1964/12 (unpublished).

Van Bastelaer, D. A. (1883).—Sur un fulgurite formé en presence de plusieurs témoins à Gougnies près de Charleroi. *Bull. Acad. Roy. Sci. Brux.*, 6 (3rd Ser): 144-152.

Wicke, W. (1859).—Directe Beobachtungen über Entstehung von Blitzröhren. *Ann. Phys.*, 106: 158-159.

Winchell, A. N., and Winchell, H. (1956).—*"Elements of Optical Mineralogy Part II. Descriptions of Minerals"*. (4th Ed.) (Wiley, New York).

Wood, R. W. (1910).—Experimental study of fulgurites. *Nature, Lond.*, 84: 70.